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# Using Complementary Models-Based Approaches for Representing and Analysing ATM Systems' Variability

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## ABSTRACT

Large-Scale Socio-Technical Systems, such as Air Traffic Management (ATM), are organizations where different interconnected systems work together to achieve a common goal. Analysis of variability is particularly challenging in these systems of systems due to the non-linear and complex interactions among social and technical functions. This paper proposes a systematic approach able to represent and to reason about the variability of such socio-technical systems. The proposed approach is based on the synergistic use of 3 models able to represent the variability from different points of view. This federation of models focusses the analysis on the relevant aspects of the systems of systems at different levels of granularity. The models taken into account for the representation of system variability are FRAM [12] focusing on organizational functions, HAMSTERS [17], which is centred on human goals and activities and ICO [20] which is dedicated to the representation of systems' behaviour (including the user interface). The paper presents a detailed development process describing how the models are built and analysed. This process is exemplified on a case study involving the AMAN (Arrival MANager) system.

## Categories and Subject Descriptors

D.2.2 [Software] Design Tools and Techniques - Computer-aided software engineering (CASE), H.5.2 [Information Interfaces and Presentation]: User Interfaces - Interaction styles.

## Keywords

ATM, Automation, Variability, Federation of Models

## INTRODUCTION

Use of models has been very successful in recent years to describe, investigate and predict the behaviour the systems operating all around us and understand the interactions between the elements that compose these systems especially in the area of computer-based systems [27]. Models can be

built with different objectives in mind. UML for instance targets at the engineering of computing systems and thus support for code production is of prime importance. When dealing with socio-technical systems objectives for using models are more widespread and cover supporting the understanding of the system, assessing its overall performance ... This paper targets at a specific objective consisting in the investigation of possible sources of variability that could affect this system and change its behaviour. The assessment of variability consequences could be particularly challenging in the context of Large-Scale Socio-Technical Systems (LSSTS) such as Air Traffic Management (ATM), where different interconnected systems work on the achievement of a common goal. The LSSTS are characterized by multiple levels of complexity, by the involvement of multiple domains and by tight interleaving of social and technical functions for successful organizational performance [10]. In particular, this interaction is partly linear and partly non-linear making it a complex and hardly predictable relationship [26]. Since early studies of sociotechnical systems [1] it was evident that, in this kind of open systems, the solution to one type of problem – beyond a certain point – depends upon solving some of the others.

The multiple levels, the overall complexity and the level of uncertainty idiosyncratic to these systems' behaviour and interactions have a strong impact when trying to model them. In particular, efforts to build an overall model to support the analysis of the systems of systems have not been very successful until now. An emerging alternative approach has been to combine modelling techniques offering different perspectives of the system under study. Such approach results in the production of several models making it possible to analyse them at different level of granularity. However, developing a model of such systems means to sweep a huge range of parameters over a vast number of possible scenarios to identify the most salient uncertainties, regions of robustness, and important thresholds of the system [7].

The aim of the paper is to look for a systematic approach to reason about variability of LSSTS. The overall objective is to overcome the limits of a single model by integrating models able to investigate such variability from different perspective. The models provide various perspectives able to cover the characteristics of the different interacting

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complex components concurring to the achievement of the whole system of systems' goals. However, these multiple views on the same system must be consistent and overlapping as little as possible in order to reduce duplication of work. To this end, the approach presented in this paper proposes a federation of several models. To demonstrate the ability of the models integrated in our approach to deal with variability of LSSTS we have applied it on a case study taken from the ATM World. The case study specifically deals with the assessment of the variability induced the introduction of increased level of automation (one of the main driver for SESAR [25]) in ATM.

Indeed, one of the main challenges in the future of Air Traffic Management (ATM) is the achievement of increased level of operational and staff productivity by means of advanced automation tools. However, increase of automation introduces variability in the system especially when automation failures or malfunction are taken into account. Such high potential of variability calls for methods, techniques and too to assess and to reason in a systematic way about variability of the overall system performance when automation degradations will occur.

The paper is structured as follows: section 2 arguments the needs and advantages to involve multiples models (dealing with system aspects, human aspects and organizational aspects) and how complementary ones can better support description and analysis of LSSTS. It also proposes a generic framework integrating those models in order to assess and reason about variability. Section 3 introduces HAMSTERS, ICO and FRAM, three description techniques offering complementary views on LSSTS. Section 4 reifies the process presented in section 2 with the 3 description techniques presented in section 3. Section 5 applies this approach to the case study of the Arrival Manager (AMAN), a computer-based support tool providing air traffic controllers with advisories for sequencing landings. Section 6 concludes the paper and presents research directions for future work.

### NEED FOR COMPLEMENTARY MODELS

Modelling approaches in the context of safety management usually focus on failure modes of technical systems and on human errors. Systems performance is generally considered as binary: the system performs as prescribed or fails to do so. In the context of complex system, perturbation can occurs not only because of components failure but also because of the interactions between the various components by affecting their resources, their time to perform, their ability to adjust to their environment, etc. In order to take into account this type of perturbations, models have to be able to address the variability of each of these components as well as the variability related to their interrelations.

On the system side, it is thus important to be able to describe the behaviour of each component and sub-component of the system ad, for each of them to identify the

sources of variability that might affect this behaviour. In order to analyse the potential propagation of this variability it is important to connect those components and to represent which facets of the component might be influenced by the upstream components.

On the user side, it is important to be able to represent the behaviour of the operators in charge of the exploitation of the system. A model must be able to capture both goals of the operators and the sequences of actions to be performed in order to reach these goals. Beyond that procedural aspects information involved in these activities have also to be represented. Indeed, they are usually involved as precondition or post conditions representing operators' knowledge or information flow from one activity to another one. Variability in terms of performance has been studied in details in particular through NASA-TLX [11] and correlates to fatigue [19], stress [5] ... but also to system failure [18].

Figure 2 presents a process made up of a set of steps for performing quantitative and qualitative analysis of a given LSSTS. The process starts by defining the scope and the objective of the analysis. Then the socio-technical system (STS) is modelled with a triple focus on human, system and organizational aspects followed by the detailed identification of variability in terms of sources and dimensions. Once the consistency of the three representations has been ensured each function identified in the STS is studied in detail. For each of these functions quantitative and qualitative aspects of variability are studied and recorded. When every function has been studied, the coupling of function (represented in the organizational model) is exploited in order to assess propagation of variability.

While many notations and descriptions techniques could be used to implement such process, we use FRAM notation, HAMSTERS task modelling technique and ICO, a Petri net-based formalism for representing respectively organizational, human and computing systems models. Next section presents this three modelling techniques. The method associated to FRAM is used as the design driver throughout the process presented in Figure 2.

### THREE COMPLEMENTARY DESCRIPTION TECHNIQUES FOR MODELING LSSTS

#### Functional Resonance Analysis Method (FRAM)

FRAM [12] is a safety management method aiming to support both accident investigation and risk assessment processes based on a set of principle related to complex socio-technical systems structure and dynamic.

First principle is "Equivalence of Successes and Failures". In FRAM models, success or failure of the performance of a function are the outcomes of the same underlying process. Second principle is "Approximate Adjustments". Conditions of work never completely match what has been specified or prescribed. Individuals, groups, and organizations normally adjust their performance to meet existing conditions. Because resources always are finite,

such adjustments will invariably be approximate rather than exact.

Third principle is “Emergence”. Variability of multiple

functions may combine in unexpected ways, leading to consequences that are disproportionately large, hence produce a non-linear effect.

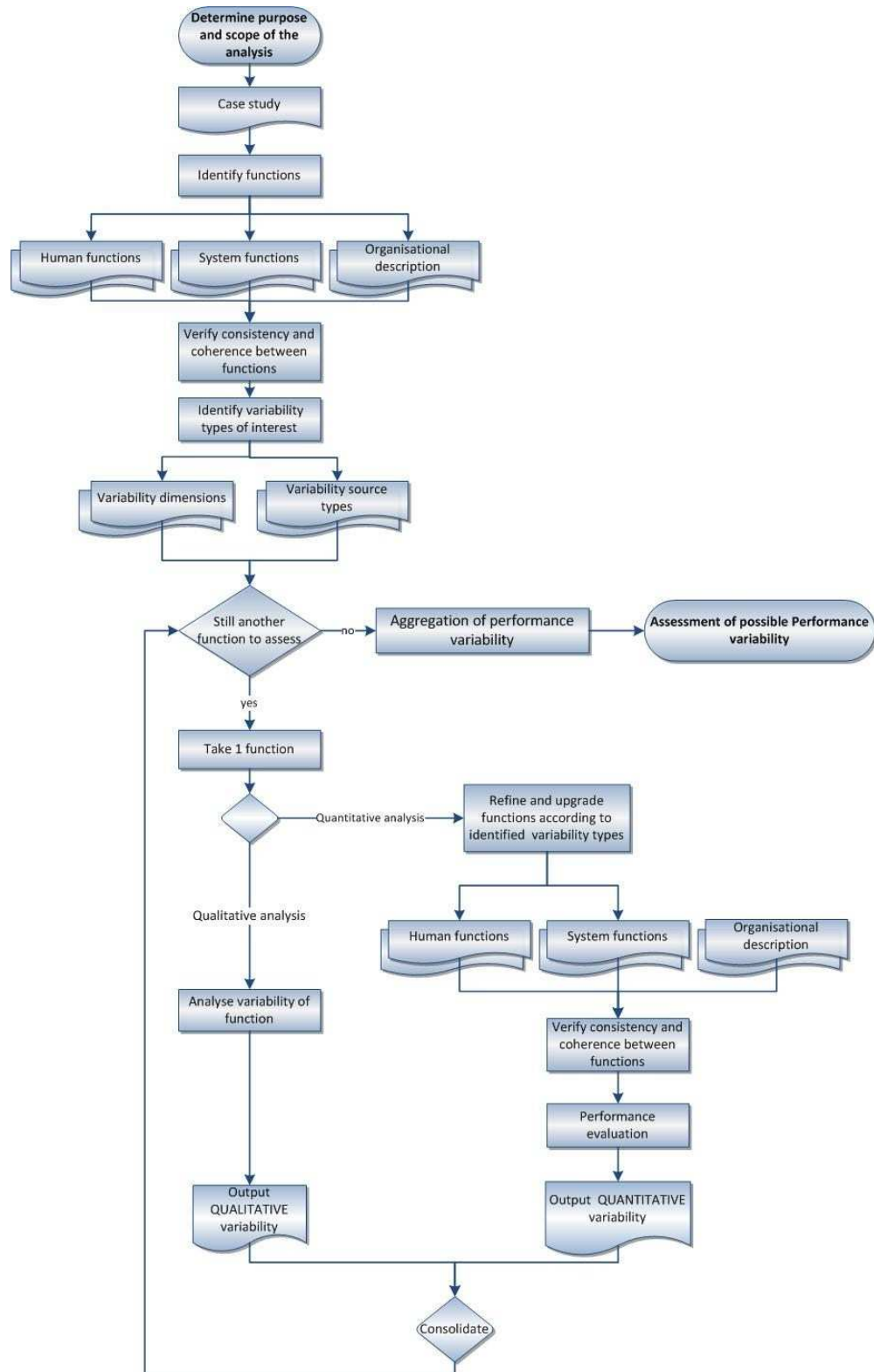


Figure 1. Abstract process to assess LSSTS performance variability

Fourth principle is “Functional Resonance”. The variability of a number of functions may every now and then resonate, i.e., reinforce each other and thereby cause the variability of one function to be unusually high. FRAM method is structured in four main phases:

- *Identify the essential functions* that are necessary (and sufficient) for the intended performance to occur (when 'things go right'). The functions can be assigned to either the set of foreground functions or the set of background functions. Characterise using the six basic aspects (Input, Output, Pre-conditions, Resources, Time, and Control). Taken together, the functions are sufficient to describe what should happen (i.e., the everyday or successful performance of a task or an activity).
- *Characterise the variability*, first as the potential of the functions described by the model, and then as the (possible) actual variability for a set of instantiations of the model. Consider whether the actual variability will be what one should expect ('normal') or whether it will be unusually large ('abnormal').
- *Identify the dynamic couplings* (functional resonance) that likely will play a role during an event. These comprise an instantiation of the model which can be used to predict how an event will develop and whether control can be lost. In relation to the traditional risk assessment, this instantiation provides an explanation of what may happen, although it does not necessarily identify unique or specific outcomes. The explanation will be based on the couplings of the variability of everyday performance, rather than failures and malfunctions.
- *Propose ways to monitor and dampen performance variability* (indicators, barriers, design/modification, etc.) In the case of unexpected positive outcome, one should look for ways to amplify, in a controlled manner, the variability rather than for ways to dampen it.

Application of FRAM method is based on a functional model where functions are describes with six aspects:

- Input (I): that which the function processes or transforms or that which starts the function,
- Output (O): that which is the result of the function, either an entity or a state change,
- Preconditions (P): conditions that must be exist before a function can be carried out,
- Resources (R): needed by the function when it is performed (Execution Condition) or consumed to produce the Output,
- Time (T): temporal constraints affecting the function (i.e. starting time, finishing time, or duration), and
- Control (C): how the function is monitored or controlled.

The definition of functional variability in FRAM is based on the principle that the variability of the output of a

function depends of the composition of three sources of variability: endogenous variability, exogenous variability and coupling variability. Variability of output can be described with a set of dimensions such as timing, precision, distance, speed, direction, force, magnitude, object, sequence or quantity. Endogenous source of variability is related to the internal variability of the system (automation, human, group or organisation) that performs the function. Exogenous source of variability is related to the variability of the environment of execution of the function (working conditions, culture, etc.). Coupling source of variability is related to the variability of functions that are coupled with the studied function.











### Human-centered Assessment and Modeling to Support Task Engineering for Resilient Systems (HAMSTERS)

HAMSTERS<sup>1</sup> is a notation designed for representing the decomposition of human goals into activities.

#### Human activity types when interacting with a system

The notation embeds several types of tasks as presented in Table 1:

TABLE 1. TASKS TYPES IN HAMSTERS

Task type	Icons in HAMSTERS task model
Abstract Task	
System Task	
User Tasks	   
Interactive Tasks	   

HAMSTERS notation proposes refined tasks for the cognitive task type:

- **Perception/working memory** modelled with a cognitive analysis task (left-hand side of Figure 2).
- **Decision making** modelled with a cognitive decision task (right-hand side of Figure 2).



Figure 2. Illustration of Cognitive analysis and decision task types

These task types have been introduced in [15] to describe in details the operators' activities while interacting with a (partly-) autonomous system.

#### Temporal ordering of activities

Temporal relationships between activities are described by operators (listed in Table 2), which help in describing task sequences performed by the user.

<sup>1</sup><http://www.irit.fr/recherches/ICS/software/hamsters/index.html>

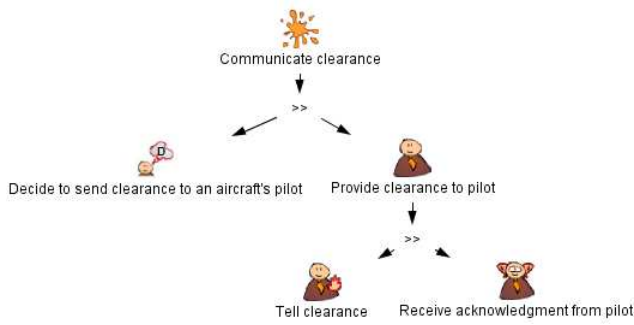


Figure 3. HAMSTERS representation of tasks for “Communicate clearance” goal

Figure 3 presents a HAMSTERS model corresponding to the decomposition in sub-tasks of the goal of an Air Traffic Controller (ATCO) for sending a clearance to an aircraft. It is composed of 4 tasks organized in a strict sequence (modelled by the operator  $\gg$ ).

TABLE 2. ILLUSTRATION OF THE OPERATOR TYPE WITHIN HAMSTERS

Operator type	Symbol	Description
Enable	$T1 \gg T2$	T2 is executed after T1
Concurrent	$T1    T2$	T1 and T2 are executed at the same time
Choice	$T1 [] T2$	T1 is executed OR T2 is executed
Disable	$T1 [ > T2$	Execution of T2 interrupts the execution of T1
Suspend-resume	$T1   > T2$	Execution of T2 interrupts the execution of T1, T1 execution is resumed after T2 has been executed
Order Independent	$T1      T2$	T1 is executed then T2 is executed OR T2 is executed then T1 is executed

Tasks can be tagged by temporal properties: *iterative*, *optional* or *both* (as graphically shown in Figure 4).



Figure 4: Icons of Optional, Iterative and both iterative and optional tasks

More precisely *iterative* refers to a task that can be executed one or several times but can be interrupted or suspended by another task. An *optional task* is a task that does not necessarily needs to be executed in order to reach the goal. The exhaustive list of operators is presented in Table 2, and is similar to the one of CTT.

#### Quantitative temporal relationships

HAMSTERS provide support to associate minimum and maximum execution time to a task (as shown in Figure 5). In this way, it enables:

- Checking temporal relevance between user’s activities and system information processing.

- Validating the developed system w.r.t. users’ performances evaluation with usage scenarios.
- Further description on the HAMSTERS and associated tool, as well as structuring mechanisms to support the effective exploitation of task models for large scale application can be found in [17].

Properties	
description	Perceive the advisories
details	
criticality level	3
optional	<input type="checkbox"/>
iterative	<input type="checkbox"/>
type	PERCEPTIVE
position	2
minimum execution time	10
maximum execution time	360
SubRoutine	
copyTask	<input type="checkbox"/>
inputports	<input type="checkbox"/>
outputports	<input type="checkbox"/>

Figure 5. Excerpt from the property editor opened on one task, with highlighted maximum execution time

#### ICO AND PETSHOP

ICO stands for Interactive Cooperative Object and is a formal notation to describe and model system’s behavior and user interactions with the system. It is Petri nets based and associated to a supporting tool, Petshop<sup>2</sup>. This tool enables to:

- Edit application behavioural models and to connect them to the presentation part of the user interface (graphical widgets and frames for example).
- Execute the application with the underlying behavioural models.

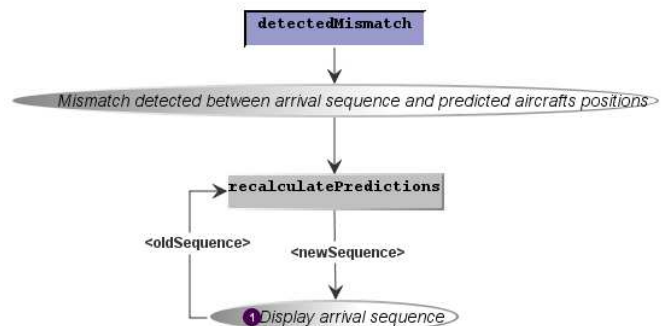


Figure 6. Extract of Arrival Manager System model with ICO notation

Figure 6 presents an extract from the ICO models describing the behaviour of an interactive application used in Air Traffic Management. This model describes the behaviour of one part of the application with a sequence of operations triggered by internal or user events. A token entering in one place (bottom shape on the figure) is used to trigger a display update on the presentation part of the application (example of such display update is presented in Figure 10).

<sup>2</sup> <http://www.irit.fr/recherches/ICS/software/petshop/>



Detailed presentation and examples of ICO and PetShop use are available at [20]. This notation and its associated tool supports fine-grain analysis of user's actions on the system, particularly with a logging function which enables performing detailed quantitative analysis [14] of user's performance with the system [21].

### INTEGRATION OF FRAM, HAMSTERS AND ICO

Objectives of the development of the Federation of Models are to provide a framework allowing the modelling of Large Scale Socio Technical Systems performance variability under different conditions, with different levels of granularity. This Federation of Models consists in integrating FRAM method with HAMSTERS and ICO

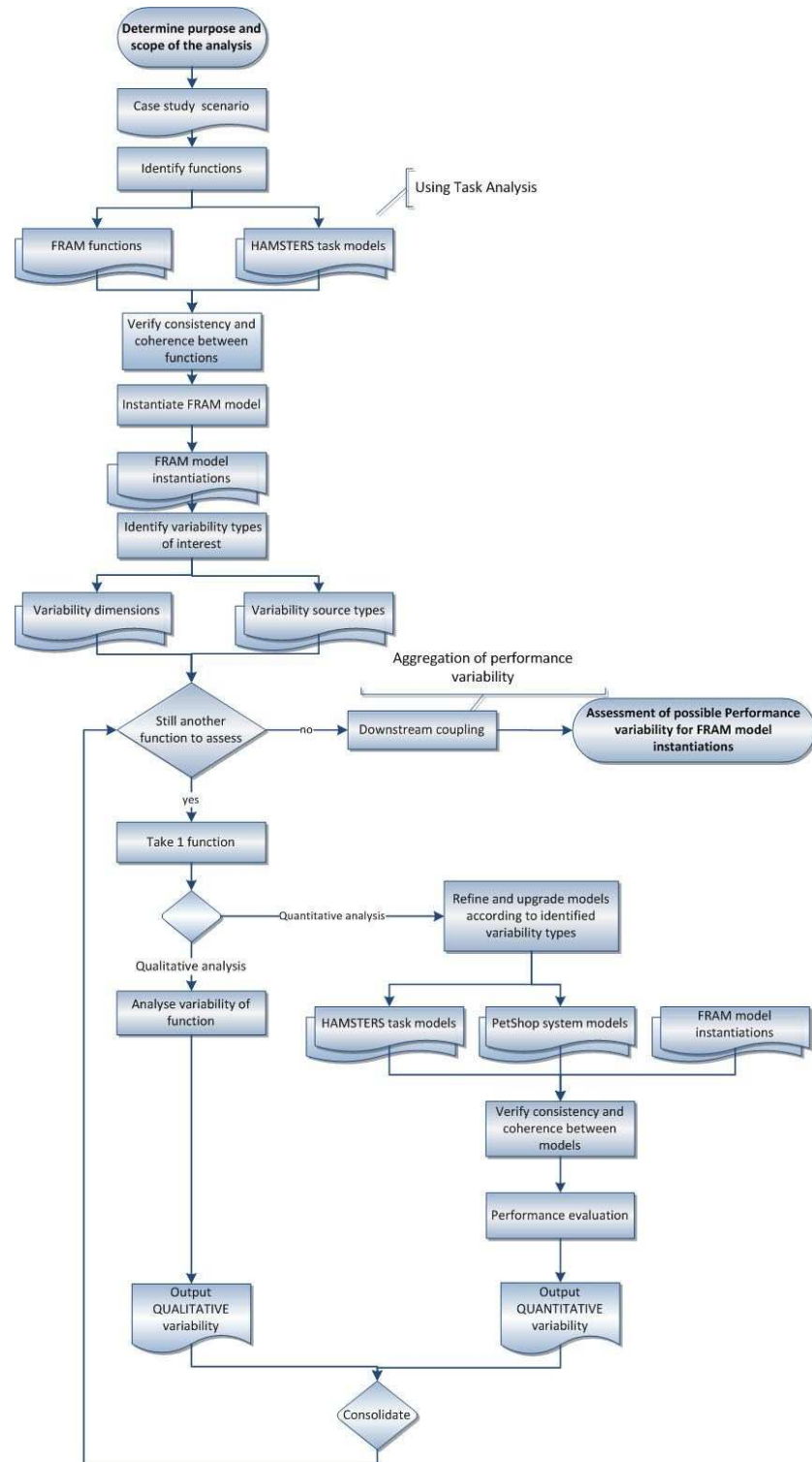


Figure 7. Federation of Models within a Models-Based process to assess LSSTS performance variability

notations and tools. The integration of FRAM, HAMSTERS and ICO leverages the high-level view on complex socio-technical systems provided by FRAM with the fine-grain view on human-system interaction provided by HAMSTERS and ICO. The main contribution is to associate performance variability analysis phase of the FRAM method with quantitative user and system performances evaluation support from HAMSTERS and ICO. Figure 1 details the proposed process putting into practice such federation of models.

This process corresponds to the reification of the process presented in Figure 2 and is detailed in the next paragraphs.

The first steps of the process (Figure 1) are dedicated to the identification of the main functions of the socio-technical system via task analysis for the FRAM application. The task analysis work is supported by HAMSTERS notation and tool... Next steps are dedicated to the variability analysis, starting by establishing the variability model of each main function according to the objectives of the socio-technical system analysis:

- Functions output variability types (temporal, precision, sequence, objects...) and sources of variability (endogenous, exogenous, and coupling) are identified.
- Relationships between sources of variability and output variability types are elaborated.

Once variability model has been established, two complementary flows can be followed:

- Original qualitative variability analysis with FRAM method (Qualitative analysis flow).
- Quantitative performance variability analysis with HAMSTERS and PetShop (Quantitative analysis flow). HAMSTERS notation and tool supports quantitative performance variability analysis on human FRAM functions and PetShop tool (with ICO notation) supports quantitative performance variability analysis on technological FRAM functions.

The last steps of the process are the original final steps of the FRAM method, performing downstream coupling analysis with data gathered from the qualitative and quantitative analysis in order to identify resonance or dampening effects.

HAMSTERS and ICO have previously been integrated to enable qualitative and quantitative analysis of coherence and consistence between user's activities and interactive system's behaviour [1]. This integration can also support automation design [16], as it enables analysing and assessing function allocation between the user and the system.

At the end of the federation process, the system under analysis will be described from three complementary perspectives:

- One based on human goals (HAMSTERS)
- One based on organisational functions (FRAM)
- One based on system's behaviour (ICO and PetShop)

### CASE STUDY: MODELLING MANAGEMENT OF AIRCRAFT ARRIVAL SEQUENCES WITH FRAM AND HAMSTERS

The first effort in integrating the models has been performed on a case study taken from the Air Traffic Management (ATM) world. It aims at demonstrating that the models can work together and, to verify that the models' integration is effective in assessing system's variability.

The future of the European ATM System is characterized by the implementation of new automated tools to solve the increase of traffic demand and new business challenges [25]. However, an accurate analysis of the problems related to possible automation degradation is still missing. The application of the federation of models to the ATM case study can provide a means to analyse the variability introduced in the system by the automation degradation, to investigate the consequences of this variability on the local and overall system performances and how these

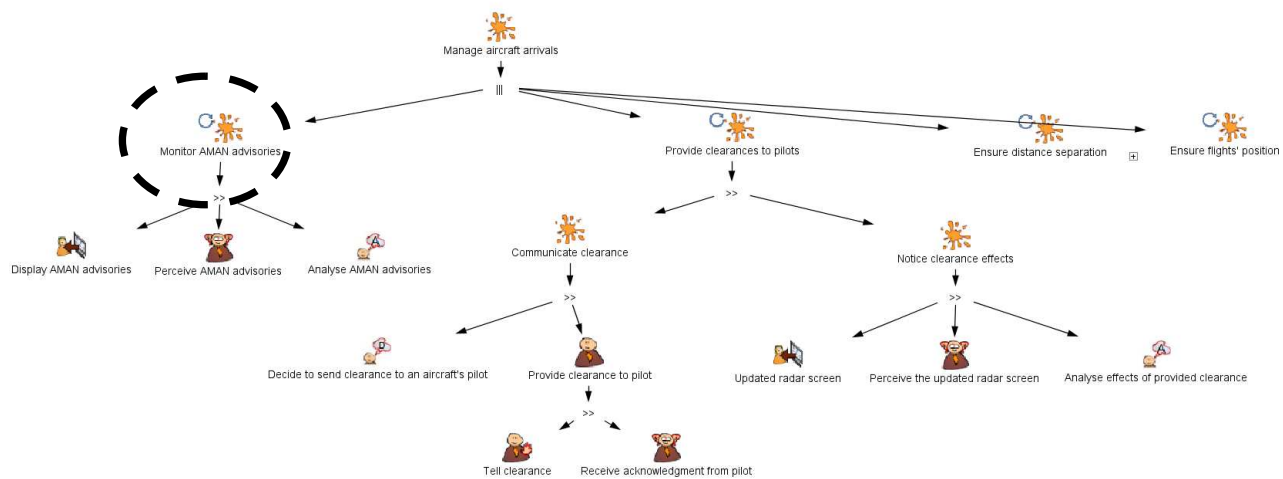


Figure 8. Excerpt of the HAMSTERS task model of the Executive controller of the Terminal Manoeuvring Area (EXC\_TMA)



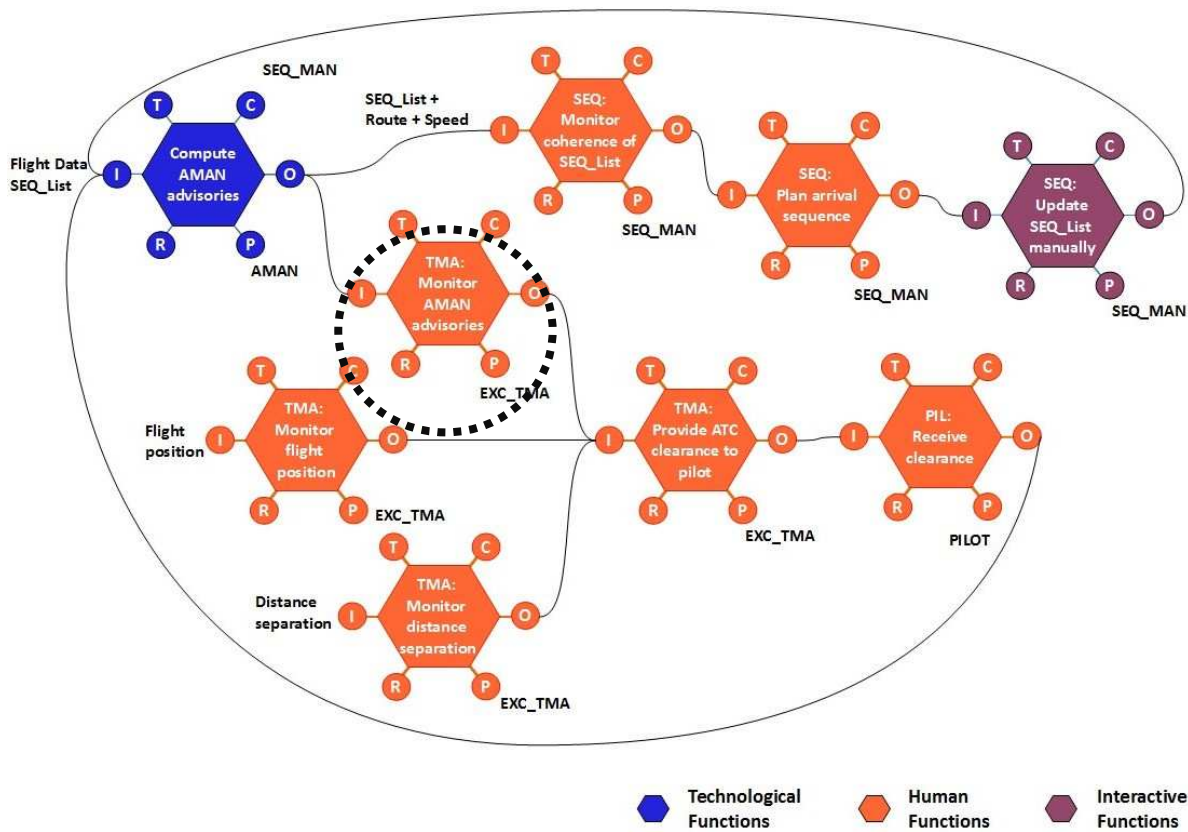


Figure 9. Excerpt of the FRAM model for the AMAN case study

consequences can propagate through the system.

#### Brief description of the case study

The extract presented in this article focuses on the AMAN tool and the EXC\_TMA, Executive Controller in the TMA (Terminal Manoeuvring Area). The TMA is the area where are controlled flights approaches and departures in the airspace close to the airport.

The AMAN (Arrival MANager) tool is a software planning tool suggesting to the air traffic controller an arrival sequence of aircraft and providing support in establishing the optimal aircraft approach routes. Its main aims are to assist the controller to optimize the runway capacity (sequence) and/or to regulate/manage (meter) the flow of aircraft entering the airspace, such as a TMA [9]. It helps to achieve more precisely defined flight profile and to manage traffic flows, in order to minimize the airborne delay, leading to better efficiency in terms of flights management, fuel consumption, time, and runway capacity utilization [16]. The AMAN tool uses the flight plan data, the radar data, an aircraft performance model, known airspace/flight constraints and weather information to provide to the traffic controllers, via electronic display, two kind of information:

- A Sequence List (SEQ\_LIST), an arrival sequence that optimizes the efficiency of trajectories and runway throughput (see Figure 10);

- Delay management Advisories, for each aircraft in the ATCO's airspace of competence.

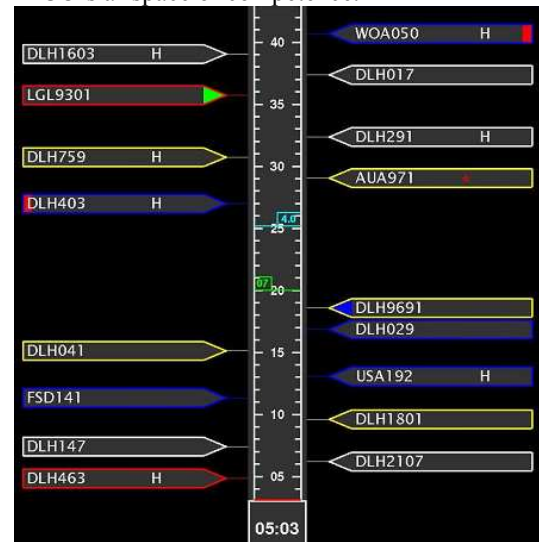


Figure 10. Screenshot of a subpart of an AMAN GUI (arrival sequence)

The EXC\_TMA is the controller deputized to handle the communications ground/air/ground, communicating to the pilots and releasing clearances to aircrafts. He/she has the tactical responsibility of the operations and he/she execute the AMAN advisories to sequence aircraft according to the sequence list.

In the proposed scenario, the pilots assume a passive role, limited to the reception and execution of the clearances.

### Identification of functions and FRAM model instantiation

As described in the process presented in Figure 7, the first steps aim at identifying functions and building a FRAM model.

Executive Controller main activities are identified during task analysis and task modelling phases. An extract of output of these phases is depicted in Figure 8, which present HAMSTERS task model of Executive Controller (EXC\_TMA) main activities. The main goals of the EXC\_TMA are to: “Monitor AMAN advisories”, “Provide clearances to pilots”, “Ensure distance separation” and “Ensure flights’ position”. These main goals are then refined into activities. The “Monitor AMAN advisories” goal, on which we focus for this case study, is decomposed in three tasks:

- “Display AMAN advisories”: an interactive output task describing that the system provides advisories (i.e. the predicted aircraft arrival sequence) to the EXC\_TMA.
- “Perceive AMAN advisories”: a perceptive user task describing that the EXC\_TMA detects the advisories provided by AMAN system.
- “Analyse AMAN advisories”: a cognitive analysis user task describing that the EXC\_TMA is cognitively processing the AMAN advisories to determine the possible clearances he/she will have to provide to aircrafts pilots.

Only the goals required for the demonstration are detailed in the presented HAMSTERS model (‘+’ symbol in Figure 8 indicate that tasks are folded, which means that subtasks are not displayed). Furthermore, the main goals are iterative and their subtasks can be performed in parallel.

FRAM method also identify AMAN systems main functions and the output of these steps is a FRAM model of the functions carried out to manage aircraft arrivals, depicted in. From this figure, we can observe that the technological function “Compute AMAN advisories” (top left corner in ) is performed by the AMAN system and outputs an aircraft arrival sequence list, which is an input for the next human function “Monitor AMAN advisories” led by the Executive Controller (EXC\_TMA). The human function “Monitor AMAN advisories” outputs clearances to aircrafts pilots.

### Performance variability analysis

After having described the AMAN system functions, a variability model is defined for each function, and qualitative and quantitative performance variability analyses are performed. The three next sub-sections detail these steps for the variability analysis between the output of the “Compute AMAN advisories” technological function and the output of the “Monitor AMAN advisories” human function (underlined with dashed circle in Figure 9). For this case study, we provide an example of quantitative performance variability assessment with HAMSTERS only,

but the application of the Federation of Models process remains the same when using ICO and PetShop.

### Establish output variability dimensions and variability source types for “Monitor AMAN advisories” function

Three dimensions are identified as relevant for the output of the “Monitor AMAN advisories” function (as summed up in Table 3): time (clearance can be performed on time, too late or not at all), precision (clearance can be precise, imprecise or acceptable) and objects (clearance can be correct or wrong).

TABLE 3. VARIABILITY TYPES ASSOCIATED TO “MONITORING AMAN ADVISORIES” FUNCTION OUTPUTS

Output	Dimensions	Variability space
Clearance for Aircraft Monitored	Temporal	On time, Too late, Not at all
	Precision	Precise, Imprecise, Acceptable
	Objects	Wrong clearance, Wrong aircraft

Sources of variability that can affect the output of the “Monitor AMAN advisories” function are gathered in Table 4. Three types of source are taken in account. Variability related to the human agent performing the function: training and experience. Variability related to the work environment of the performance: access to procedure, condition of work, etc. Variability related to the consequences of past actions performed: availability of resources, number of goals and conflict resolution, available time, etc.

TABLE 4. SOURCES OF VARIABILITY OF “MONITORING AMAN ADVISORIES” FUNCTION OUTPUTS

Output	Type of source of variability	Source of variability
Clearance for Aircraft Monitored	Endogenous	Training, Experience
	Exogenous	Access to procedure and methods, Condition of work, Crew collaboration quality, Quality and support of organization
	Coupling	HMI, Availability of resources, Quality of communication, Number of goals and conflict resolution, Available time

TABLE 5. RELATIONSHIPS BETWEEN VARIABILITY SOURCES AND OUTPUT DIMENSIONS

Variability sources	Output dimensions		
	Temporal	Precision	Objects
Training	X	X	X
Experience	X	X	X
Access to procedure and methods	X	X	
Condition of work	X	X	X
Crew collaboration quality,	X	X	
Quality and support of organization	X	X	
HMI,	X		X
Availability of resources,	X	X	X
Quality of communication			
Number of goals and conflict resolution	X	X	X
Available time	X	X	X

Finally, Table 5 highlights relationships between the output variability types and the different variability sources types, which will be used to analyse qualitatively the impact of these sources on the output variability of the function.

TABLE 6. EXAMPLE OF A QUALITATIVE ASSESSMENT OF THE OUTPUT VARIABILITY FOR THE “MONITOR AMAN ADVISORIES” FUNCTION

Qualification of the impact of the variability sources on variability dimensions	Variability dimensions		
	Temporal	Precision	Objects
Training	+	+	+
Experience	+	+	+
Access to procedures and methods	-	-	NA
Conditions of work	+	+	+
Crew collaboration quality	0	0	NA
Quality and support of organisation	0	0	NA
HMI	-	-	-
Availability of resources	0	0	0
Number of goals and conflict resolution	-	-	-
Available time	-	-	-
Output qualitative variability	Too late	Imprecise	Adequate clearance

#### Performance variability qualitative analysis

Based on the identified variability dimensions and source types, a simple qualitative assessment of performance variability can be performed. Each source of variability can impact variability positively (+1), negatively (-1) or be neutral (0). The value of the output dimension is assessed by summing up the variability sources that can affect it. For example, for the precision dimension, if the sum of the source of variability associated is between -9 and -4 value is “Imprecise”, if the sum is between -3 and +3 value is “Acceptable” and if the sum is superior to +4, value is “Precise”.

Table 6 contains an instance of a qualitative assessment of the output variability of the “Monitor AMAN advisories” function when the input coming from the “Compute AMAN advisories” function is on time but imprecise. According to the impact of variability source types on the variability dimensions, the output of the “Monitor AMAN advisories” function will be a clearance that is arriving too late and imprecise but adequate.

This qualitative assessment of variability is a support for reasoning about relationships between output variability and variability sources, in order to highlight possible coupling between functions’ outputs and detect potential resonance effects.

However, this conceptual framework does not provide support to estimate and assess quantitative values of functions’ output variability. At proposed by this article, next paragraph presents an example on how this ability can be done integrating the FRAM method with the HAMSTERS notation and tool.

#### Performance variability quantitative analysis (with HAMSTERS)

This subsection of the case study describes an example on output temporal variability measurement of the “Monitor AMAN advisories” function. It intends to measure the impact of and incomplete sequence list provided by AMAN (some Time To Loose and Time To Gain information are missing). Output temporal variability is assessed quantitatively in order to analyse how delays due to the AMAN malfunctioning will affect the monitoring advisories function output. This function is critical as its output is the input to determine ATC clearance that has to be provided to aircrafts pilots.

The starting point of this quantitative analysis is to ensure that the models built during the application of first phases of the FRAM method can be used to measure the targeted variability output type. In our case, HAMSTERS model issued by the Task analysis phase is incomplete to measure output temporal variability. The “Monitor AMAN advisories” sub-goal of the task model is then refined to

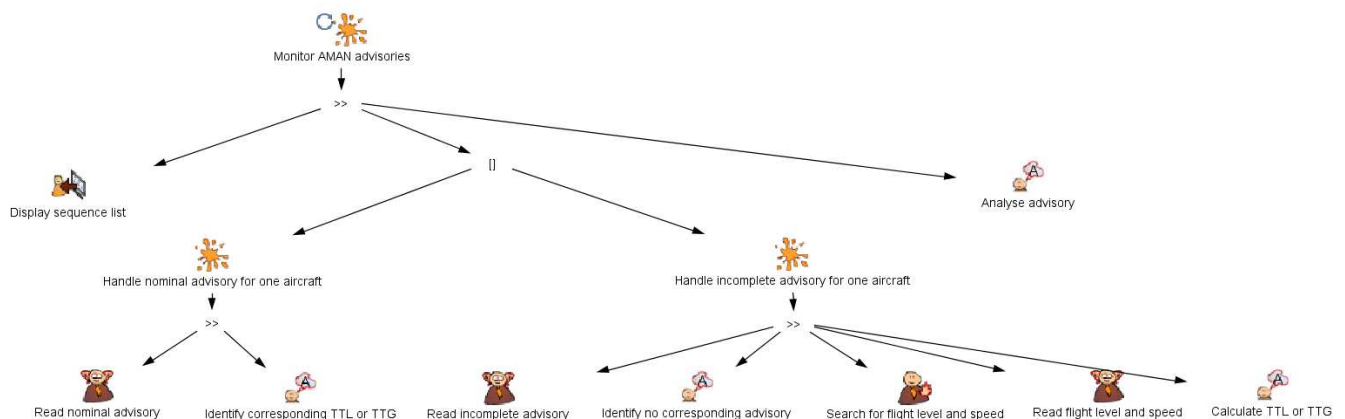


Figure 11. Refined HAMSTERS task model for the Monitor AMAN advisories goal in order to evaluate temporal variability

take into account additional tasks that will be carried out by the Executive Controller if the AMAN advisories are incomplete. The refined model is presented in Figure 11 and contains two new sub-goals: "Handle nominal advisory for one aircraft" and "Handle incomplete advisory for one aircraft". When monitoring the advisories, depending on the AMAN system status, one sub-goal OR the other will be accomplished ('[]' symbol in the task model). Each of these sub-goals is refined with tasks that have to be performed. For each of these tasks, an estimated minimum and maximum execution time is associated. These associated execution times can be filled in with statistics processed from the observation of controllers, as well as estimated values processed from human cognitive processing models (such as [2]) and Fitts' psychomotor model [1]. Such performance evaluation techniques are described in [14]. One each task has been attributed minimum and maximum execution time, total minimum and maximum execution times can be calculated in order to measure output temporal variability. Table 7 summarizes this calculus and provides the resulting variability.

TABLE 7. MAXIMUM AND MINIMUM EXECUTION TIME OF THE "MONITOR AMAN ADVISORIES" FUNCTION

Tasks and sub-goals	Min exec. time (ms)	Max exec. time (ms)
Task "Read nominal advisory"	2000	5000
Task "Identify corresponding TTL or TTG"	1000	7000
<b>Total for sub-goal "Handle nominal advisory"</b>	<b>3000</b>	<b>12000</b>
Task "Read incomplete advisory"	2000	5000
Task "Identify no corresponding advisory"	3000	8000
Task "Search for flight level and speed"	3000	15000
Task "Read flight level and speed"	2000	6000
Task "Calculate TTL or TTG"	5000	10000
<b>Total for sub-goal "Handle incomplete advisory"</b>	<b>15000</b>	<b>44000</b>
Task "Display sequence list"	500	1500
Task "Analyse advisory"	3000	10000
Total for "Monitor AMAN advisories" with nominal advisory	6500	23500
Total for "Monitor AMAN advisories" with incomplete advisory	18500	55500
<b>Output temporal variability of function "Monitor AMAN advisories"</b>	<b>12000</b>	<b>32000</b>

As indicated in Table 7, according to task model and time estimations for each task, it takes between 6,5 and 23,5 seconds to monitor an advisory when receiving a complete advisory from AMAN, whereas it takes between 18,5 and 55,5 seconds to monitor an advisory when receiving an incomplete advisory from AMAN. Temporal output variability range is then from 12 to 32 seconds.

### Aggregation of variability and downstream coupling

Beyond the relatively simple results exhibited in previous sections the proposed approach aims at assessing variability for large scale socio-technical systems. Such systems are made up of a lot of interconnected functions influencing each other. As depicted in Figure 7, once the output variability assessment has been performed for each function, it is possible to aggregate and combine these results in order to identify potential resonance and dampening effects. Additionally, if quantitative assessments are performed for each function of a downstream flow, it makes it possible to assess precisely if the possible output variability of one function may compromise the achievement of a downstream function, and thus, potentially, the achievement of one goal of the LSSTS.

To come back to the case study presented in previous section, variability on the time constraints for communicating the clearance to the pilots, it then can be assessed whether as the AMAN malfunctioning may compromise the overall traffic management and trigger flight cancellation. Temporal output variability can be assessed and compared to the time constraints imposed to the overall ATC.

### CONCLUSION AND FUTURE WORK

This paper has presented a notation-supported process for the analysis of variability of large scale socio-technical systems. This process has been demonstrated on the AMAN (Arrival Manager) case study involving automated behaviour. We have focused on the output temporal variability related to the degradation of AMAN as timing is an easy concept to present. However, many other sources (see Table 4 for a list related to the case study) of variability have to be taken into account in order to assess the performance and the safety level of the overall system.

The application of the process on a subset of real-size case study exhibits directions for future work. One of them is to design and develop tools to support FRAM models edition and simulation as currently offered by PetShop and HAMSTERS. This is one of the objectives of the SPAD project together with the integration of this new tool within PetShop suite. Such an integrated tool suite will not only support the editing of models but also the assessment of their compatibility (no conflicting information is present) as well as their simulation. This is of critical importance if variability has to be assessed in a systematic way as, due to propagation, many functions can be impacted by the evolution of a single source of variability in one function.

The AMAN computer function is rather simple and the sources of variability are rather limited. Accounting for more complex computing systems as defined in SWIM will require more in-depth representation of computing functions in FRAM and more complex ICO models.

Finally, more explicit handling of human error (as in [22]) or barriers identifications and description (as in [4]) will be part of the next steps of the approach. Indeed, within SPAD

project and as presented in [13] the approach will be tested on two different case studies: the AMAN one presented above and one dealing with Unmanned Aerial Vehicles (UAV) in order to assess its applicability if different levels of automations are under consideration.

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